

First Results of Testing 3.9 GHz TM₀₁₀ Superconducting Cavity

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Abstract—Fermilab is developing third harmonic 3.9 GHz superconducting cavity to improve performances of A0 and TTF photoinjectors. In frame of this project we have built and tested two nine-cell copper models and one 3-cell niobium cavity. Properties of the high order modes were carefully studied in a chain of two copper cavities at room temperature. In paper we discuss results of cold tests of the 3-cell cavity before and after BCP.

Index Terms—Superconducting RF cavity, Higher Order Modes, Accelerating gradient.

I. INTRODUCTION

Third harmonic 3.9 GHz cavity was proposed to increase the peak current of the bunch and reduce emittance in the new generation of the high brightness photoinjectors developing for the future large scale accelerators like XFEL and Linear collider [1], [2]. In TTF-2 (DESY) and upgraded Fermilab photoinjectors [3] the third harmonic accelerating section will be installed after the first TESLA module with eight 1.3 GHz cavities and before the first bunch compressor. Section will correct non-linear distortions in the longitudinal phase space due to cosine-like 1.3GHz cavity voltage to improve bunch performance after compression. Four cavities with a reasonably high accelerating gradient can provide total required voltage ~ 20 MV/m (5 MV/cavity). Fermilab is developing 3rd harmonic cavity and cryostat for the four cavities [4]-[9]. Status and the first results of our studies are discussed in this paper.

II. CAVITY DESIGN AND STATUS

Third harmonic cavity is made of nine cells with elliptical shape in iris and equator areas. First design of the cavity was proposed in [4], and then was modified [5]. Regular cells have 30mm iris diameter, while the end cells iris from the tube side was increased up to 40mm in diameter for better coupling with the power coupler and better damping of the higher order modes (HOM). Two HOM couplers are mounted in both ends of the cavity to provide good damping of the parasitic modes. The general view of cavity with ports for power coupler and

pick-up antenna and build-in HOM couplers are shown in Fig.1. The cavity main parameters are shown in Table I. To study HOM performances of the cavity and properties of accelerating mode we have built two full-scale copper models, each equipped with the power and HOM couplers. The results



Fig. 1. Geometry of the naked 9-cell 3.9 GHz cavity.

of studying the dipole modes in cavity we are discussing in next chapter. We also built short 3-cell niobium cavity for the low temperature high gradient tests in the vertical cryostat. The building of the first nine-cell cavity is planning to finish by the end of 2004. After performance test in the vertical cryostat, cavity will be assembled with the helium vessel and frequency tuner, and then will be tested with the beam in the horizontal cryostat at Fermilab photoinjector. Helium vessel and frequency tuner are in procurement; power coupler and horizontal cryostat are under design.

TABLE I. Third harmonic cavity parameter list

Active Length	0.346 m
E _{acc}	14 MV/m
Phase	-179 deg
R/Q	375 Ohm
E _{peak} / E _{acc}	2.26
B _{peak} / E _{acc}	4.84 mT/(MV/m)
Q _{external}	9.5e+5

III. HIGHER ORDER MODES

Higher order modes in the superconducting cavity, if they not damped, will cause beam break up (BBU) instability, which kick beam out to the wall. HOM studying is a big issue for the 3rd harmonic cavity. Each cavity has two HOM couplers with appropriate orientation to soak out both polarizations of the parasitic modes. Power coupler also works effectively for the mode extraction. Simulations of the single cavity performance by using HFSS, MAFIA, MWS and

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Analyst software, show that the loaded Q-value for some of the HOMs is sensitive to the boundary conditions at the end of the tubes [8]. In HFSS simulations cavity was excited by the artificial RF antennas placed in each cell to imitate beam current. As for boundary conditions at the end of tubes, we have applied electric, magnetic or dissipative walls. Sensitivity to the boundary conditions means that loaded Q-value will strongly depends of power reflection from the neighbor cavity. For experimental studies of the HOM damping in chain of cavities we have built two copper models (Fig.2). HOM couplers and end-tubes are mounted on the cavity by using rotatable flanges, which allow adjust the coupler-to-coupler and antenna orientations in order to get



Figure 2: Two copper cavities assembled for HOM measurements on the bead-pull set-up.

maximum dissipations. Both cavities were tuned to get right frequency (3.9GHz) and good field flatness.

The results of calculated BBU threshold for Q_{ext} and measured data for single cavity and two assembled cavities are

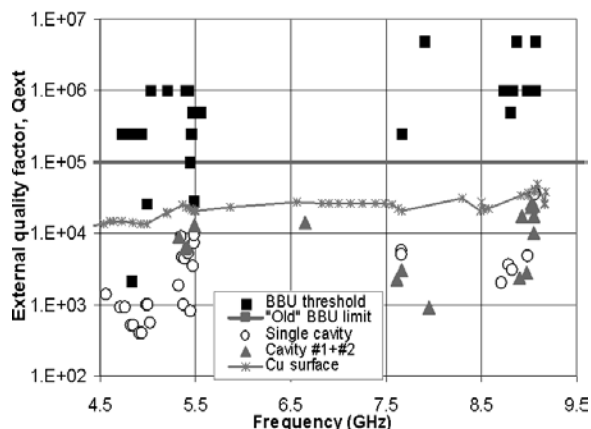


Fig. 3. Quality factor vs. frequency for the dipole higher order modes in cavity. Black boxes represent BBU threshold, calculated for 1nC bunches in TTF-2 photoinjector, circles and triangers – measured Q in a single and chain of two copper cavities. Crosses – calculated Q-value for the copper cavity.

shown in Fig.3, where loaded Q-value of the dipole mode is

plotted vs. frequency. BBU threshold was calculated for the TTF2 beam parameters for more dangerous dipole modes with the transverse $(R/Q) > 1 \text{ Ohm/cm}^2$ [10]. As one can see that measured Q-values are well below the BBU threshold for all modes up to 8.5GHz. Measured Q-values for a few modes from the 5th passband (frequency ~9 GHz) were limited by the power dissipation in copper surface ($Q \sim 10^4$), it means that in

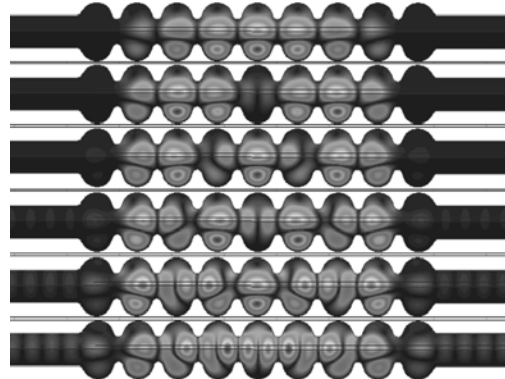


Figure 4: "Trapped" dipole modes from the 5th passband.

niobium cavity Q might be much higher. Our calculation show, that those modes have very small fields in the end-cells and tubes and practically are trapped in cavity (Fig.4). Fortunately, taking into account low R/Q for those modes and good coupling of the HOM coupler to the tube (measured coupling is better than 10dB for both polarizations), the estimated loaded Q-values are still below BBU threshold. Table II shows external Q-value of "trapped modes" in cases when RF power dissipated in beam pipes or extracted by HOM couplers with 10dB coupling. Here was not taken into account additional dissipation of the dipole modes in power coupler. As one can see from the Table II., 5th passband is very narrow and the field distribution for each mode is sensitive to the cell frequency errors, so even small perturbations in cell dimensions can easily disturb the field distribution for those modes and change R/Q value. We are

TABLE II. HOM couplers Q_{ext} calculated data.

Frequency, MHz	R/Q, Ohm	Q, BBU limit	Q_{ext} , Loaded beam tubes	Q_{ext} , HOM couplers
9054.03	0.002	2.0e9	2.29e6	2.29e7
9054.70	0.05	8.0e7	5.76e5	5.76e6
9056.21	0.061	6.6e7	2.11e5	2.11e6
9059.49	2.17	5e6	7.81e4	7.81e5
9067.36	4.053	1e6	2.57e4	2.57e5
9089.07	0.565	1e7	1.08e4	1.08e5

planning further studying of the trapped modes, including cold test in the vertical dewar.

IV. COLD TESTS OF THE 3-CELL CAVITY

Niobium three-cell cavity (Fig. 5) was tested at 2K for the several times. The initial "calibration" test was done after cavity production but before any surface treatment, except

degreasing and ultrasonic cleaning. First and second sets of testing were done after cavity treatment at JLAB. The applied treatment procedures are described below.

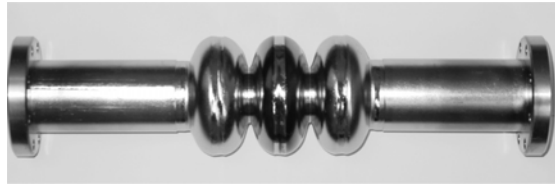


Fig. 5. Three-cell niobium 3.9GHz cavity

A. Cavity treatment.

After production the cavity passed two BCP treatment at JLAB by Peter Kneisel. During the first time the following treatments were applied to the cavity:

- *Degreasing* in detergent under ultrasonic agitation. The cavity was immersed in cleaning solution, app. 30 min.
- *External 20 μ m BCP*. Cavity was immersed in freshly mixed BCP solution of HF/HNO₃/H₃PO₄ in a ratio of 1:1:1 and dipped for a total of 3 min (rate $\sim 7 \mu\text{m}/\text{min}$); after each min the cavity was rinsed to avoid overheating.
- *Internal 20 μ m BCP*. The cavity was filled with fresh acid and cooled by an external water bath. After 1 min, the acid was removed and the cavity was rinsed. It was repeated 3 times, then cavity was disassembled, dried and the frequencies were measured. Removing material was estimated from frequency control with calculated coefficient 85 kHz/micron.
- *Heat treatment*. The cavity was loaded into the furnace for heat treatment during 10 hours at 600°C.
- *Internal material removal* was performed in the same way as described above. Between each additional BCP step (2x1min), the cavity was turned 180° to average out the additional etching of the lower cells due to the filling of the cavity with acid. Frequency was measured after each step. From the frequency measurements it appears that ~ 83 micron have been removed after seven steps; from the time and the measured etch rate app. 140 micron have been removed, indicating a non-uniform removal.
- *High pressure rinsing* with 1200 psi for 15 min at two axial locations.
- *Drying, assembling*. The cavity was dried in the class 10 clean room and closed with stainless steel blanks after they had been blown off in front of a particle counter with nitrogen gas.

After series of vertical cold tests done the cavity was treated for the second time (light BCP) with the following procedures:

- 3x1 min BCP ($\sim 16 \mu\text{m}$) with rinsing in between drying
- Add. 3x1 min BCP (cavity upside-down)
- HPR in 3 axial locations (each cell) for ~ 10 min each.
- Cavity dried in class-10 clean room for drying (24 hrs).
- Assembled with cleaned and dried Teflon blanks.

B. Surface Resistance vs. Temperature.

After surface treatment cavity was assembled at FNAL in class-10 clean room. Low-power adjustable input coupler and

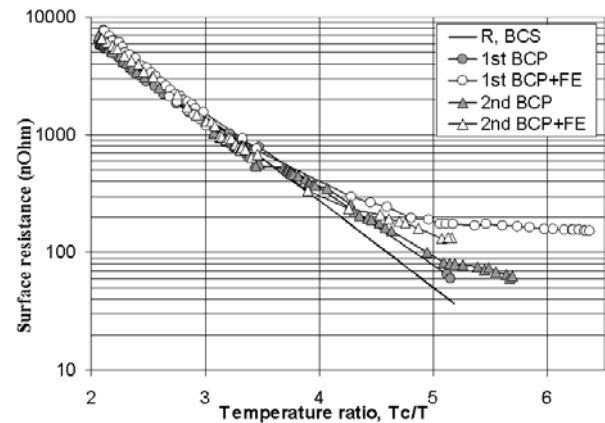


Fig. 6. Surface Resistance vs. Temperature. Triangles – after first surface treatment, circles – after second treatment. In both cases surface resistance was degraded after working with strong field emission (see open triangles and circles).

pick-up antenna were mounted and the cavity was closed with UHV vacuum flanges and pumped out. The performance test was carried out in the vertical bath cryostat filled with helium. In test we have measured the time constant of the cavity, which is determined by the loaded quality factor Q_L . The position of the coupler antenna was adjusted to minimize power reflection, then $Q_L \approx Q_0/2$. When cavity is operated in pulse regime, Q-value can be computed from the time decay. The first set of measurements was done at low power level during the cool down from $\sim 4^\circ\text{K}$ to 1.8°K . The results of measurements are presented in Fig 6. Resistance was calculated as $R_s = G/Q_0$, where $G = 291 \Omega$ is the geometrical factor for the 3-cell cavity. After first surface treatment we have reached $R_s \sim 60 \text{ n}\Omega$, not faraway from the theoretical BCS value. During the performance test done at 1.8°K the cavity showed strong field emission for the accelerating gradients more than 10MV/m. After working at high gradient with a heavy X-ray level, the surface resistance dropped down on the following tests. After second 20 μm BCP treatment surface resistance was restored to the same level, but after reaching the field emission regime, resistance increased again as it was in the first set of cold tests.

C. High field performances

High gradient performances of the 3-cell cavity measured for π -mode are shown in Fig. 7. Achieved gradient $\sim 12.5 \text{ MV/m}$ was limited by X-ray due to field emission, not quench. Surface-to-acceleration field ratios for the 3-cell cavity are: $E_s/E_{acc} = 2.765$ and $H_s/E_{acc} = 5.7 \text{ mT}/(\text{MV/m})$, which is quite different from those for the 9-cell cavity (see Table I).

D. Other modes.

The same set of measurements was done for 0 and $\pi/2$ -

modes in this cavity. For 0-mode electric and magnetic fields in the mid-cell almost twice higher than in the end-cells, while

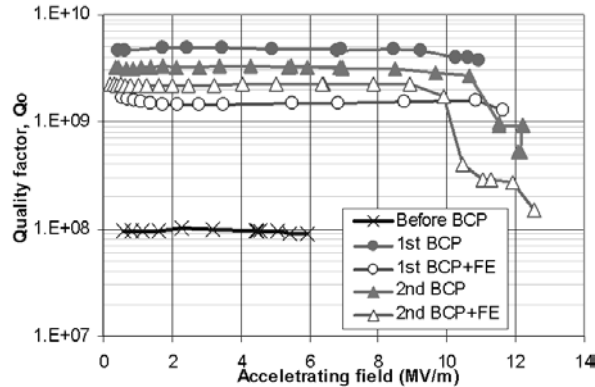


Fig. 7. Performance of the 3-cell cavity before surface treatment (crosses), after 1st (triangles) and 2nd (circles) BCP treatments. Open triangles and circles shows Q degradation in the following tests after working with strong field emission.

for $\pi/2$ mode mid-cell is almost empty, all fields are concentrated in the end-cells (Fig. 8). So, different cavity behavior at these modes gives us information, which cell causes problem. The measured surface magnetic fields before quench was found 110; 85; 77mT for 0; $\pi/2$ and π modes, which corresponds accelerating fields $E_{acc} \sim 22$; 17; 16MV/m in the 9-cell cavity: (Design parameters are: $E_{acc} = 14$ MV/m; $B_{surf} = 68$ mT). Maximum value of the magnetic field ~ 110 mT (0-mode) achieved in the middle cell is probably limited by the thermal breakdown threshold, as was

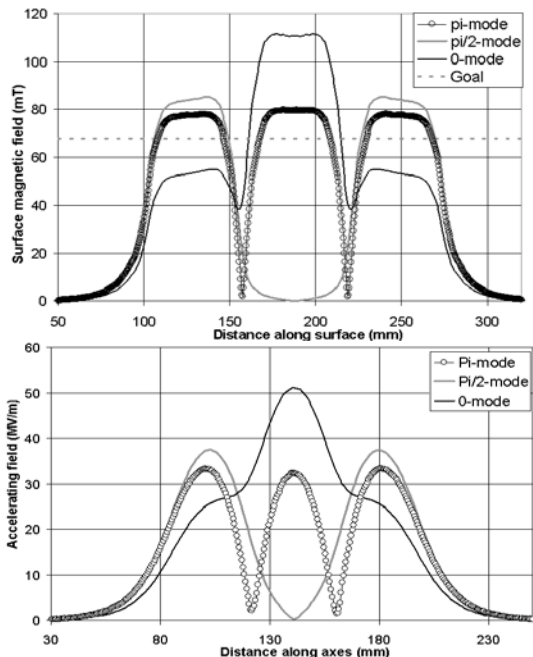


Fig. 8. Surface Magnetic (top) and the axial Electric fields (below) in the cavity for 0, $\pi/2$, π modes.

predicted by our calculation. Performances of the $\pi/2$ and π modes were limited by one of the end-cell. Visual inspection made after first set of cold tests discovered few “rusted” spots \sim few mm^2 in size on one of the end-cell iris from the tube

side. It might explain our results. Second BCP treatment didn’t remove completely contamination and we are planning repeat surface treatment and cold test.

V. CONCLUSION

In frame of SRF R&D Fermilab is working on 3.9GHz cavity. To develop SRF technology and study cavity performances we have built and tested two copper 9-cell cavities and niobium 3-cell cavity. All cavities were tuned after production to get right frequency and field flatness. Higher order modes were investigated in a single copper model and in the chain of two cavities. The results of measurements are in a good agreement with simulations. Few trapped modes were found in the 5th passband as predicted, but their loaded Q-values are below BBU threshold. Because trapped modes are very sensitive to the errors in cell dimensions needs more studies on the final cavities to understand limitations.

Superconducting performances of the three-cell cavity were studied in the vertical cryostat. Measured surface resistance ~ 60 nOhm at 2K is close to BCS prediction. Achieved level of the surface magnetic field ~ 110 mT exceeds requirements. Although we exceeded our goal, the accelerating gradient was limited by the field emission. Further surface treatment hopefully will help to improve cavity performance.

By the end of this year we hope to built first 9-cell niobium cavity, including helium vessel, frequency tuner and magnetic shielding.

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